Timing of magnetic reconnection initiation during a global magnetospheric substorm onset

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Abstract. We have used a unique constellation of Earth-orbiting spacecraft and ground-based measurements in order to study a relatively isolated magnetospheric substorm event on August 27, 2001. Global ultraviolet images of the northern auroral region established the substorm expansion phase onset at 0408:19 (±1 min) UT. Concurrent measurements from the GOES-8, POLAR, LANL, and CLUSTER spacecraft allow us to construct a timeline which is consistent with magnetic reconnection on the closed field lines of the central plasma sheet near X_{GSM} ~-18 R_E some 7 minutes prior to the near-earth and auroral region times of substorm expansion phase onset. This suggests that magnetic reconnection (i.e., the substorm neutral line) in this case formed in the mid-tail region substantially before current disruption, field dipolarization near geostationary orbit, or auroral substorm onsets occurred. Thus, the magnetic reconnection process is interpreted as the causative driver of dissipation in this well-observed case.

Introduction

It is a longstanding issue in magnetospheric substorm physics to understand where and exactly when key substorm processes initiate [e.g., *Baker et al*, 1996]. One point of view is that very near-Earth (6-8 R_E) instabilities lead to cross-tail current disruption and auroral brightening, and then magnetic reconnection occurs subsequently in the mid-tail (20-30 R_E) region [e.g., *Lyons*, 2000]. On the other hand, a case studied in detail using

Geotail, geostationary Earth orbit (GEO), and ground-based data provided considerable evidence that magnetotail reconnection began prior to the near-Earth and auroral onsets of activity [*Ohtani et al.,* 1999]. What has been needed to help further clarify this issue is more well-observed cases and a better observational platform configuration.

With the successful launches of the four-satellite CLUSTER constellation [*Escoubet et al*., 1997] and the IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) spacecraft [*Burch,* 2000], a new era of space physics research is at hand. When CLUSTER and IMAGE data are combined with POLAR, ACE, GOES, and ground-based elements of the International Solar Terrestrial Physics (ISTP) program, we truly have the long-sought "telescope-microscope" combination that has been required to address substorm problems [see *Baker and Carlowicz*, 1999]. In this paper we present a case study of a substorm onset which utilizes the new tools mentioned above. This event is interpreted to show that magnetic reconnection began slightly Earthward of CLUSTER some 7 minutes prior to the auroral brightening (and current disruption) that has often been used to define substorm expansion phase onset.

Overview of August 27, 2001 Event

As shown by the small inset in Figure 1, the period early on August 27, 2001 had a particularly propitious arrangement of spacecraft. The Advanced Composition Explorer (ACE) was directly upstream of the Earth at ~240 R_E geocentric distance and it continuously measured the solar wind speed (~400 km/s) and the interplanetary magnetic field (IMF). Inside the magnetosphere, there were several spacecraft at geostationary orbit bearing Los Alamos (LANL) particle sensors or NOAA magnetometers (GOES). The most favorably-positioned geostationary spacecraft was GOES-8 which was just premidnight at ~0400 UT. The POLAR spacecraft was near its apogee of 9 R_E and was located near 0200 LT and about 2 R_E above the GSM equatorial plane at ~0400 UT on this day. Finally, the CLUSTER constellation of spacecraft were just slightly postmidnight at 0400 UT and were very near the $Z_{GSM}=0$ plane. Not shown in the inset is the IMAGE spacecraft which was positioned above the northern pole of the Earth.

Figure 1 has several data panels. Figure 1a shows the composite ACE solar wind-IMF parameter, VB_z, which is a measure of solar wind energy coupling to the magnetosphere [see *Baker et al.,* 1996 and references therein]. The ACE data have been shifted by 59 min to account for propagation time to Earth. The value of VB_z went negative (i.e., became geoeffective) shortly after 0200 UT and stayed negative, with some fluctuations, until ~0430 UT. Figure 1b shows the auroral electrojet index AE(=AU-AL). The Canadian sector was in an ideal location for this event and a growth phase extending from ~0230 to ~0400 UT was observed in CANOPUS data. A large auroral onset was seen in AE at ~0410 UT. This substorm expansion phase onset time was very consistent with the dipolarization of magnetic fields seen at GOES-8 (and the subsequent "current disruption" shown in panel 1c). The injection of $E \gtrsim 100$ keV electrons during this substorm onset is shown in Figure 1d: Given that s/c 1994-084 was located at 11 LT, the injected electrons were quite dispersed in energy. Test-particle simulations (not included here) show that both energetic ions and electrons were injected earthward from ~18 R_E and reached geostationary orbit at ~0408 UT.

The lower four panels of Figure 1 show data from POLAR and CLUSTER. Figure 1e shows an H^+ energy-time spectrogram from the TIMAS experiment on POLAR [*Shelley et al.,* 1995]. The H^+ data show a dropout to lobe-like conditions at ~0330 UT and a powerful return of higher-energy fluxes at ~0422 UT. Figure 1f shows the E>0.75 MeV channel from the high-energy electron sensor telescope (HIST) on POLAR [Blake et al., 1995] and it is clear that the plasma sheet recovery at 0422 UT seen by POLAR was accompanied by relativistic electrons. Finally, the lower panels (Figures 1g and 1h) show H^+ and O^+ spectrograms, respectively, from the CLUSTER Ion Spectrometry (CIS) experiment [Reme et al., 1997] on CLUSTER 1. It is seen from these data that C1 was persistently in a hot, H^+-dominated plasma sheet from ~0200 UT until ~0410 UT. There was a plasma dropout (into a more lobe-like environment) from ~0410 UT until ~0425 UT and there was then a return to a more tenuous hot plasma sheet until at least 0500 UT.

Details of Expansion Phase Onset

From the above broad overview, it is clear that a relatively long substorm growth phase occurred in this case extending from at least ~0230 UT to ~0400 UT. The electrojet index data and the GOES-8 data (panels 1b and 1c) suggest several small onset events which we interpret as pseudobreakups [e.g., *Nakamura et al.*, 1994]. These were most prominently seen at ~0305 UT, ~0325 UT, and ~0345 UT. However, only the ~0408 UT onset seemed to produce a major substorm onset at GEO or on the ground. In Figure 2 we present far ultraviolet (FUV) data from the IMAGE Wideband Imaging Camera (WIC) experiment [*Mende et al.*, 2000]. These data are extremely important to help establish global substorm characteristics.

We have carefully gone through WIC data using the available 2-min cadence of sequential images from 0200 UT through 0500 UT. Figure 2 shows a representative selection of images that reveal the main auroral results. During the period ~0220 UT to ~0400 UT, the polar cap (open flux) region generally grew in area as would be expected during an extended growth phase [e.g., *Baker et al.*, 1996]. As noted in the prior paragraph, there were hints in other data that a pseudobreakup probably commenced at ~0345 UT. This was seen in the WIC auroral images: Small brightenings occurred at 0345 UT, these intensified in a limited way until about 0400 UT, and then this pseudobreakup activity subsided without developing into a full expansion phase. This same timing of pseudobreakup activity was clearly seen in individual CANOPUS ground magnetometer records (data not shown).

At ~0408:19 UT, WIC images showed dramatic brightening of auroral features (Figure 2e) right at local midnight and also around 20 LT. In the subsequent 10-15 min (Figures 2f-2h), the aurora showed a large expansion phase and breakup. By ~0430 UT, the substorm had clearly progressed toward a recovery phase. Thus, the IMAGE/WIC data support ground-based and GOES-8 data indicating that a substorm expansion phase started between the 0406:16 and 0408:19 UT images. Energetic neutral atom (ENA) images from IMAGE (not shown here) also support this onset timing.

Having established the substorm onset timing, we examined more detailed data from instruments onboard the several CLUSTER spacecraft (which we abbreviate C1 through C4). The locations of the CLUSTER s/c and their relative spacing is shown in the small inset toward the bottom of Figure 3. We see that C1 was closest to the Earth while C3 was slightly lower in Z_{GSE} than were the other three s/c.

Figure 3 has several main panels. Figure 3a and 3b shows the plasma flow moments (3a) and magnetic field components (3b) obtained from C1 for the period 0330 to 0500 UT. The (X,Y,Z) components of flows are shown, respectively, by black, red, and green curves. The lower four panels of Figure 3 show data from all four CLUSTER s/c according to the color coding (black, red, green, and blue) shown below panel 3d. In order, the data shown are: Figure 3c, energetic electron fluxes (E>30 keV) from the RAPID experiment [*Wilken et al.*, 1997]; Figure 3d, plasma moments in the Earthward-tailward sense from the CIS experiment [*Reme et al.*, 1997]; Figure 3e, magnetic field north-south component from the FGM experiment [*Balogh et al.*, 1997]; and Figure 3f, electric field dawn-dusk component from the EFW experiment [*Gustafsson et al.*, 1997]. (Note in Figure 3 that CIS velocity moments and electric field data were not reliably available from C2).

Figure 3 data taken together make several notable points. First of all, during the pseudobreakup period after ~0345 UT, there was only a brief burst of Earthward plasma flow. How this relates, and possibly maps, to associated auroral features seen by IMAGE is a fascinating issue that we will address in a future paper. Otherwise, all of the CLUSTER s/c continued to be embedded in a rather tenuous plasma sheet until well after 0400 UT. The relatively large value of B_x (figure 3b) and the small values of B_y and B_z show that the s/c were in the outer parts of a (probably) fairly thick plasma sheet. Clearly the most interesting activity for all of the CLUSTER s/c began at ~0400 UT. At that time, B_x diminished substantially while first B_y and then B_z became negative (see panels b and e). At ~0401 UT all of the spacecraft saw strong tailward plasma flow (V_x ~ -500 km/s) and a small burst of energetic electrons (3c). By about 0406 UT, the magnetic field had rotated northward (and more Earthward) again and the plasma flow was by that time strongly Earthward. By ~0410 UT, the several CLUSTER s/c had moved into a nearly lobelike environment based on the RAPID/IES electron fluxes reaching background levels (Figure 3c), but even in the northern tail lobe there were some field-aligned bursts of plasma ions (compare panels 3a, 3d, and 3f).

At ~0422 UT, the plasma sheet apparently expanded abruptly and re-enveloped all four of the CLUSTER s/c. As shown by IES data (Figure 3c) the first s/c to be enveloped was C3, which was the one closest to the neutral sheet. C4 was the farthest from the Earth and was the last to be enveloped. The plasma flow (3a and 3d) and electric field (3f) data show very strong Earthward flow in the recovering plasma sheet (0422-0430 UT).

Figure 4 provides an even more detailed view of key data for the period 0352 UT to 0425 UT. Panel 4a shows magnetic field data for the B_z component for the four CLUSTER spacecraft (again color-coded). Panel b shows the Earthward-tailward flow moments (for C1, C3, and C4). Panel c shows details of the GOES-8 magnetic field data for the parallel (Hp, green), Earthward (He, red), and normal (Hn, black) components. Figures 4a and 4b show interesting differences between various individual s/c. Overall, however, the combined, four-spacecraft data show a positive excursion in B_z at ~0401:30 UT followed by an interval of southward B_z (which lasted until ~0406 UT). During most of this time there was moderate to strong tailward plasma flow. At ~0406 UT the plasma flow switched to sunward (Earthward) flow and B_z became more northward in orientation.

Notice in Figure 4c that there was a brief, small amplitude oscillation of the magnetic field at GOES-8 that commenced at ~0401 UT. This was almost "Pi 2-like" in character. However the major GOES-8 field dipolarization occurred at 0409 UT (±30 s). After the dipolarization, there was an interval of ~2-min duration with strongly fluctuating field which is usually identified as "current disruption" [e.g., *Takahashi et al.*, 1987].

Interpretation and Discussion

Based on the wide range of data available in this case, we would conclude that, by the usual indicators, a substorm expansion phase onset occurred at ~0408 UT on August 27, 2001. This substorm led to a major auroral brightening and breakup, a field dipolarization at geostationary orbit, energetic particle injections (also at GEO), and ground magnetic bay signatures in a broad local time sector. In the period 0408~0410 UT there was a very evident disruption of the cross-tail current near 6.6 R_E geocentric distance. What is important about the present event is that we had POLAR observations available at X~-9R_E, and, especially, CLUSTER multipoint measurements at X=-19R_E. The latter data showed very suggestive evidence that magnetic reconnection commenced at ~0401 UT in the central plasma sheet at X~-18R_E. This reconnection was of apparent broad spatial extent and it persisted for several minutes.

From the many data sources available, we suggest the broad picture of events on August 27 as shown in Figure 5. As illustrated in Figure 5a, the magnetosphere went through a clear, prolonged growth phase during the period ~0230 to ~0400 UT. During this phase, the polar cap grew in size (IMAGE/WIC data) and the magnetotail became more stretched and stressed (POLAR, GOES, and ground data). There were several pseudobreakups during the growth phase, but IMAGE data suggest that only the ~0408 UT onset led to a full substorm development. As shown in Figure 5b, we conclude that at ~0401 UT there was onset of magnetic reconnection in the central plasma sheet at X~-18R_E (CLUSTER data). We conclude that the observed dissipation was reconnection because of the negative magnetic field orientation and strong convective ($\vec{E}$x$\vec{B}$) plasma flow. Over the course of several minutes, the plasma flow reversed direction and the magnetic field became northward. Thus, we suggest that the magnetic reconnection site (X-line) moved tailward past the CLUSTER constellation. From careful examination of the four individual CLUSTER spacecraft data sets, we calculate that the X-line moved tailward at ~100 km/s during the time interval 0405 to 0407 UT.

It is likely that the magnetic X-line progressed from reconnection of closed (plasma sheet) to open (lobe) field lines at ~0408:30 UT (Figure 5c). In this interpretation, it is the explosive increase of reconnection rates that accompany lobe field reconnection (with the concomitant large Alfven speeds in the inflow region of the X-line) that marks the expansion phase of the substorm (as seen in the auroral and ground-based data). This time would also mark the pinching off of the substorm plasmoid (Figure 5c). The progression of reconnection from closed plasma sheet field lines to the eventual reconnection of open field lines is an important aspect of the near-earth neutral line (NENL) model [*Baker and McPherron*, 1990; *Baker et al.*, 1996].

As a final step, and again in good comport with the NENL model, the plasma sheet rapidly expanded during the substorm recovery phase. This is illustrated in Figure 5d. We note that both POLAR and CLUSTER sensors saw the plasma sheet recovery sequence quite well. Careful comparison of POLAR data (Figure 1) and CLUSTER data (Figure 3) show that POLAR observed the plasma sheet slightly earlier than CLUSTER. Thus the plasma sheet "thickening" front progressed tailward from POLAR (-9 R_E) to CLUSTER (-19 R_E) at high speed. As noted in conjunction with the discussion of Figure 3 above, we are able to use the multi-spacecraft RAPID data to calculate the plasma sheet expansion velocity at the CLUSTER location.

In summary, we note that many authors have concluded [see *Lyons*, 2000 and references therein] that substorms initiate in the very near-Earth portion of the plasma sheet (6-8 R_E) and that mid-tail magnetic reconnection is a consequence, not a cause, of this near-Earth onset process. It is therefore important to realize that for at least some well-observed cases such as the one presented here [see, also, *Ohtani et al.,* 1999] magnetic reconnection and magnetotail energy dissipation apparently begin well before near-Earth and auroral effects. We look forward to using the described telescope-microscope combination to further illuminate the relation between auroral, near-Earth, and mid-tail processes during many more substorms.

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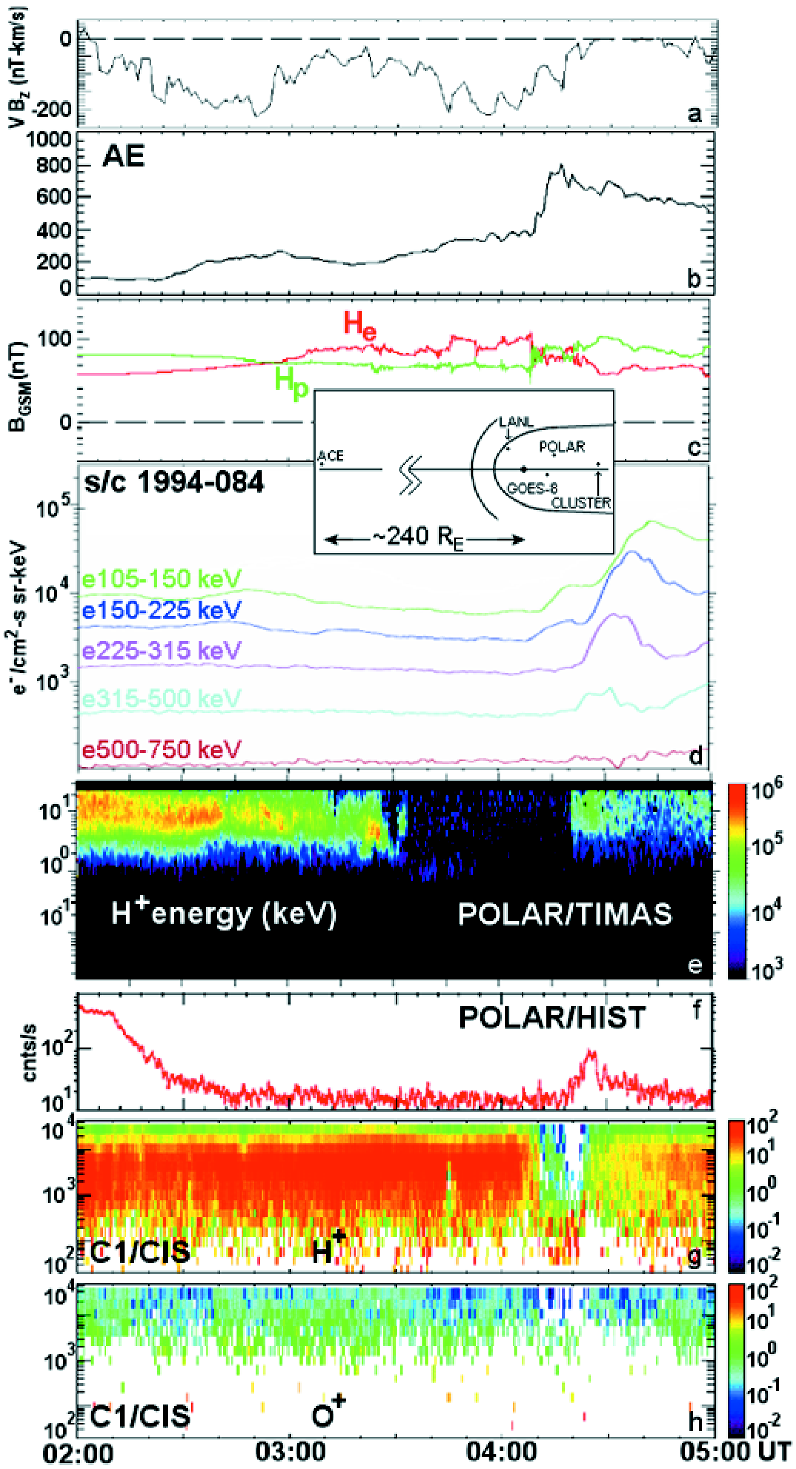

Figure 1. Multipoint overview data for the period 0200-0500 UT on August 27, 2001; (a) VB_z from ACE; (b) Auroral electrojet indices; (c) GOES-8 magnetic field data; (d) LANL energetic electron data, 50-500 keV; (e) POLAR/TIMAS H^+ data; (f) POLAR/HIST electron flux; (g) CLUSTER s/c #1 H^+ data; and (H) CLUSTER 1 O^+ data.

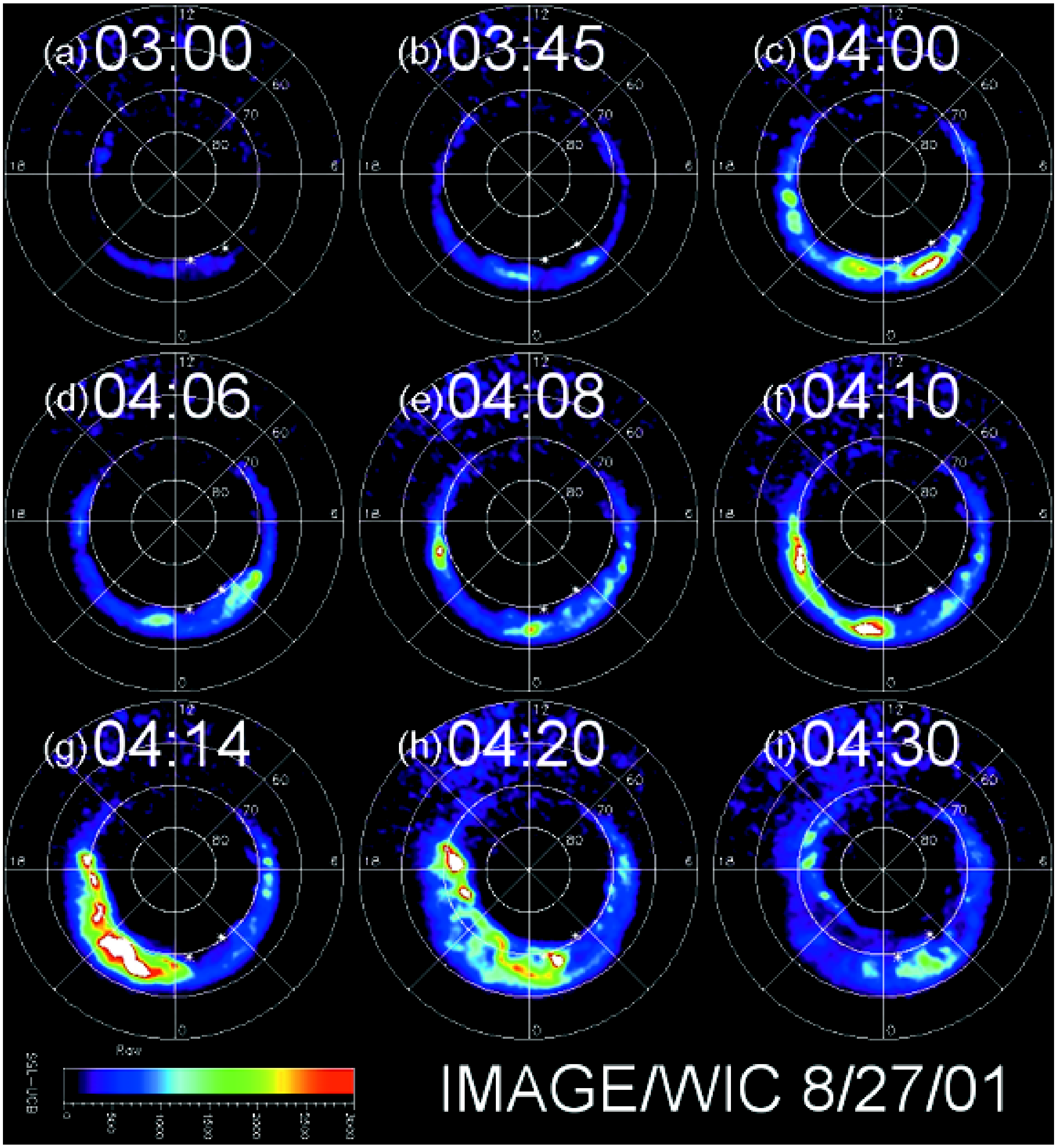

Figure 2. Selected IMAGE Wideband Imaging Camera (WIC) far ultraviolet images for the times shown on August 27, 2001.

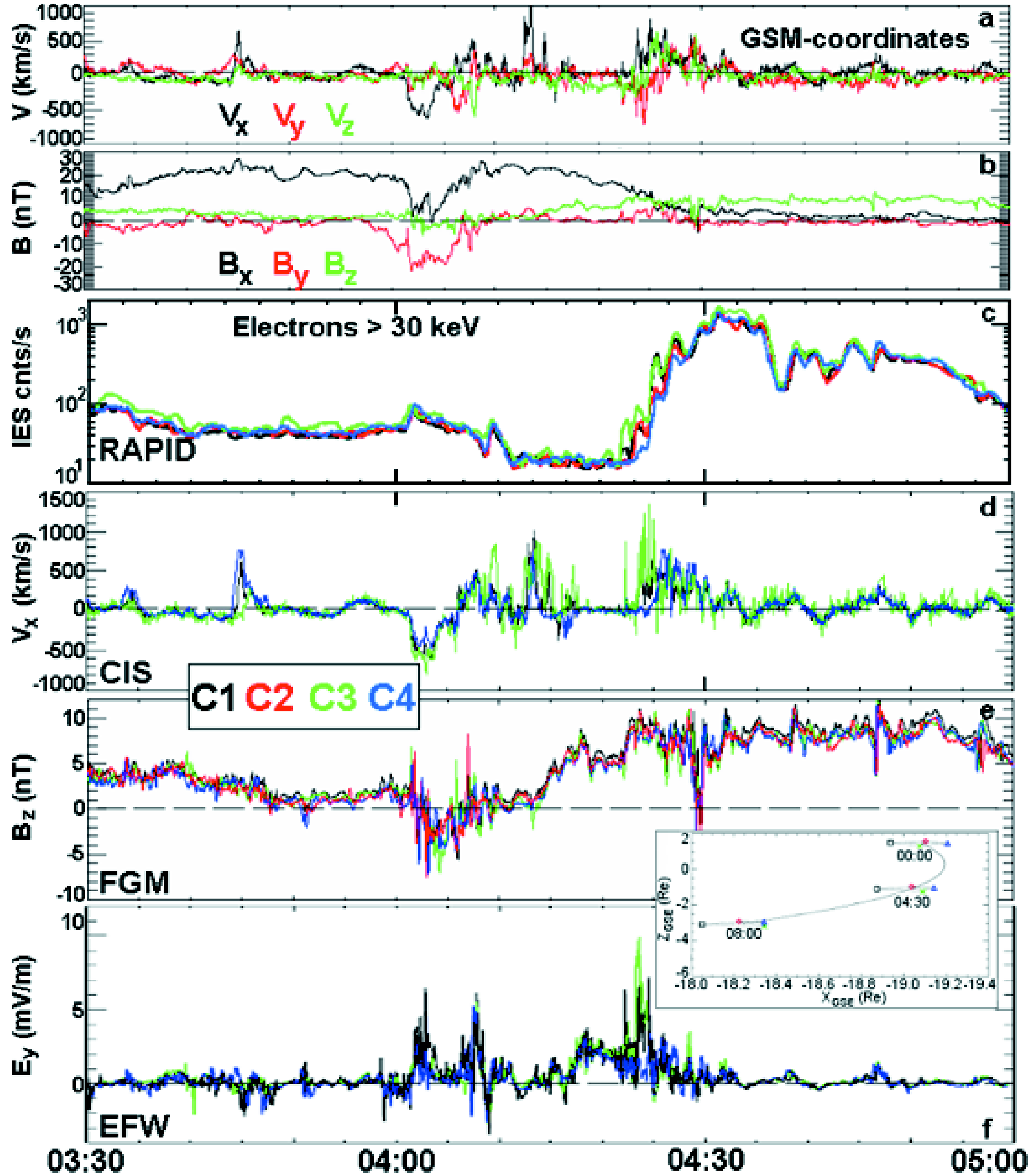

Figure 3. Details of CLUSTER data (as described in the text) for the period 0330 to 0500 UT on August 27, 2001. The small inset between panels (e) and (f) shows the CLUSTER constellation position.

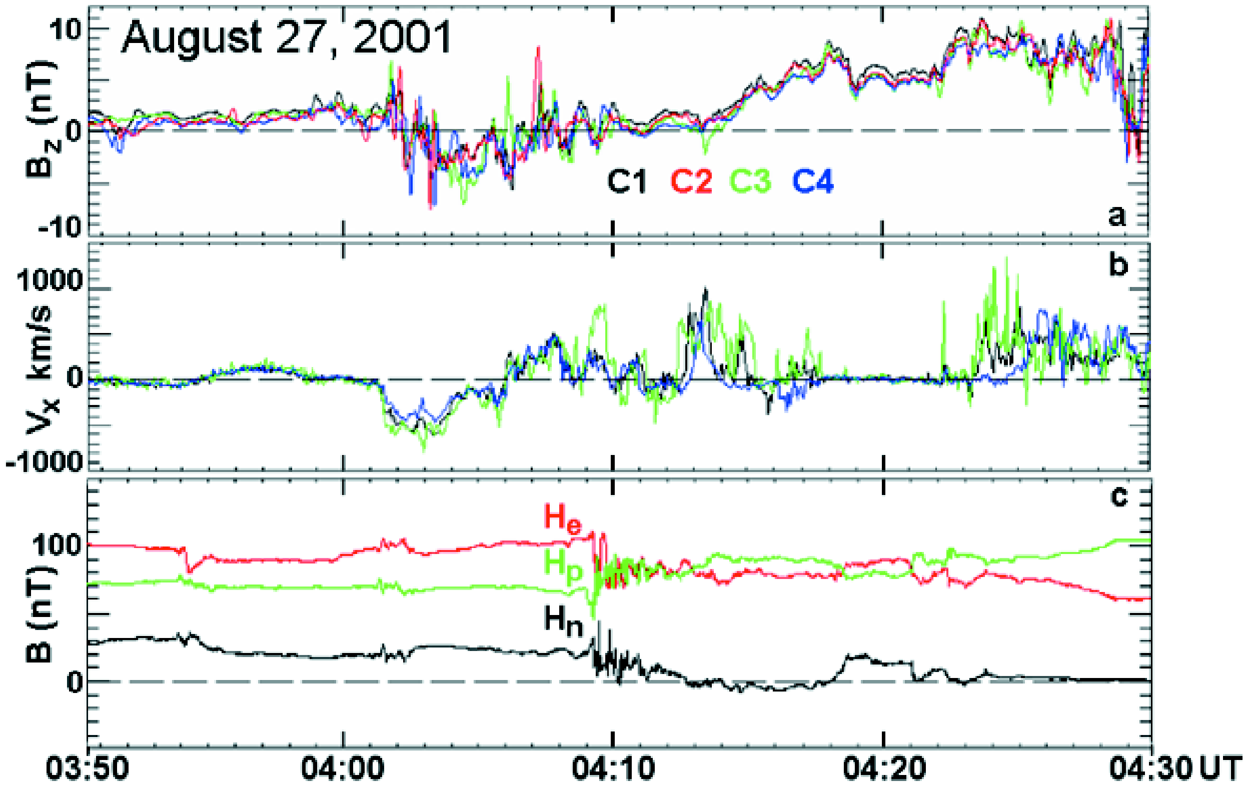

Figure 4. (a) Magnetic field Z_{GSM} – component data for the four CLUSTER spacecraft for the period 0352 to 0425 UT on August 27, 2001. Data for each spacecraft are color-coded as shown; (b) Plasma flow moments in the X_{GSM} direction for C1, C3, and C4; (c) GOES-8 magnetic field data (as described in the text).

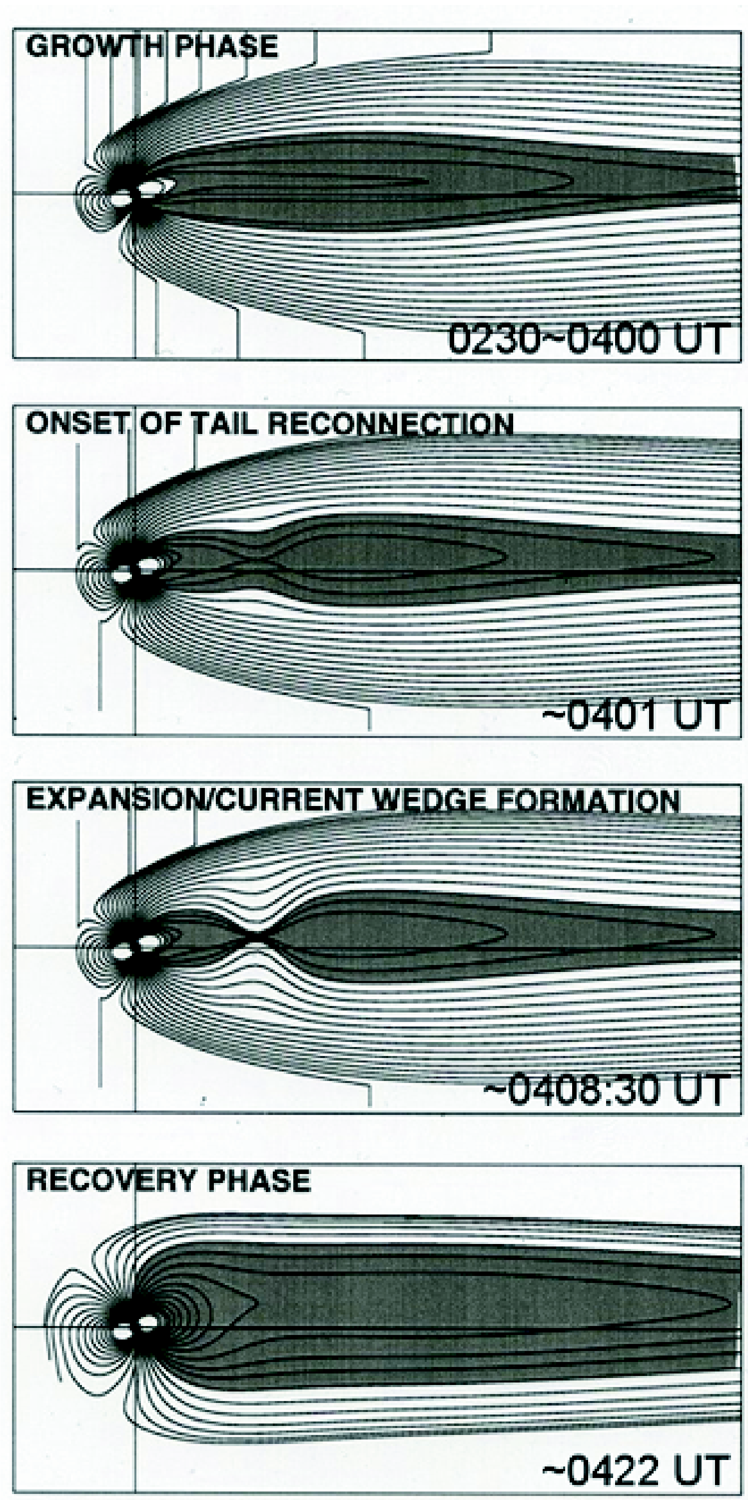

Figure 5. A summary of the substorm sequence as seen for August 27, 2001: (a) The growth phase (0230-0400 UT); (b) The onset of tail reconnection (0401 UT); (c) Expansion phase (0408 UT; (d) Recovery phase (0422 UT).